Bots for Lethal Places

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1. Introduction

One of the types of places that are definitely chief non-human environments are the last two words in this paper's title. Although these places are sparce around human-ocupied areas on Earth's surface, others are actually created by humans. These include most high radiation environments like those inside nuclear reactors. Your author is uniquely qualified to write about the nukes. Why, let me give you a clue: the first two positions I was employed at after graduating from Texas Tech University with my BSEE was as a controls engineer with Rockwell Atomics International (AI) in Southern California, and as a Facilities Engineer for GE Nuclear's Vallecitos Nuclear Center (VNC), not too far from my primary residence from which I am writing this (Livermore, CA).

I'm not too sure what happened to Rockwell AI, but, since it's right down the road, I know that VNC is being decommissioned. However, the Nuclear Industry is in the midst of a revival. See my post from earlier this year summarized and linked below for details on this resurgence:

US Nuclear Power, Current Status: *Although I started my career in the nuclear industry, most of it was spent in the electric utility SCADA, and similar markets. However, it has always apparent to me that we need nuclear power, and more of these base-load generators need to be built in future years. Thus, when I happened upon reference 1 below, I was pretty sure that I would spin a post from this paper. However, this document is very detailed, so this paper will only be a brief summary, but readers that are interested in nuclear power, might consider bookmarking the link at the end of this page.*

https://www.energycentral.com/nuclear/post/us-nuclear-power-current-status-xwNPd6Lkakv6JET

2. Modern Electronics for Nuclear Environments

In more recent years I've worked in non-nuclear jobs, and then retired about a decade ago. Before retiring, I worked for a company with HQ in Europe, Siemens, that was actually very similar to GE, and I'm now a Siemens Retiree. One of the business areas I worked at with Siemens (actually with Landis & Gyr, a Siemens subsidiary), was supervisory control and data acquisition (SCADA) systems which were our primary products at Landis & Gyr Systems. Over the years I worked on SCADA systems that operated in many harsh environments, but never nuclear. The problem is that modern micro-electronics are nuked (pun intended) by the neutron flux in nuclear environments rapidly degrading the materials and interfaces therein unless these electronics are expressly designed for the high-radiation environment hosting them or heavily shielded.

As I mentioned in the Intro and the prior paragraph, I'm an electrical engineer who works with SCADA Systems. This technology is very heavily dependent on modern electronics. As an Electrical Engineer, I am a member of IEEE, and receive a copy of IEEE-Spectrum every month. In my June copy was a brief article that stopped me cold.[1]

[1] Katherine Bourzac, IEEE Spectrum June Edition, "Wi-Fi Receiver can Survive Inside a Nuclear Reactor" https://spectrum.ieee.org/robotics-in-nuclear-industry

2.1. Electronics that can Survive inside a Reactor

Researchers have made a Wi-Fi receiver that's tough enough to work inside a nuclear reactor. They hope the receiver might be part of a wireless communications system for robotics used to decommission reactors.[2]

Yasuto Narukiyo, a graduate student at the Institute of Science Tokyo, presented the wireless receiver at the IEEE International Solid-State Circuits Conference (ISSCC), in San Francisco in February. The receiver endured a total radiation dose of 500 kilograys,[3] *orders of magnitude higher than the doses typically tolerated by electronics in space.*

After the 2011 nuclear disaster at the Fukushima Daiichi plant, engineers began using robots to help characterize and clean up the site. Most of these require LAN-cables that can get tangled, says Narukiyo. His team, which includes his advisor Atsushi Shirane and Masaya Miyahara of Japan's High Energy Accelerator Research Group (KEK), is aiming to develop a wireless system for controlling robots in this harsh environment.

Even under less drastic circumstances, nuclear plants don't last forever, and they need to be dismantled and decontaminated so the sites can be reused. This process risks exposing people to radiation, thus the use of robots.

The need for such robots is growing. Per a 2024 study, of 204 reactors that have been closed, 11 plants with a capacity over 100 megawatts have been fully decommissioned, and 200 more reactors will reach the end of their lifetimes in the next 20 years.

While electronics for space exploration are typically required to endure radiation doses of 100 to 300 grays over three years, a robot operating in a nuclear reactor needs to endure more than 500 kGy over the course of six months, says Narukiyo—at least 1,000 times the dosage. A robotic arm made by KUKA was able to withstand just 164.55 Gy of damage before failing. For comparison, the lens of the eye absorbs just 60 milligrays during a CT scan of the brain.

2.2. Radiation Hardening

To "harden" the 2.4-gigahertz Wi-Fi receiver against intense levels of radiation, Narukiyo and his team changed its mix of components, minimized the total number of transistors, and tinkered with the geometry of the transistors that were left.

The group also considered the differences in how radiation affects PMOS transistors, MOSFETs in which current is carried primarily by positive charges, and NMOS, in which it is carried by electrons. PMOS transistors are more vulnerable to radiation damage because positive charge gets trapped in both the oxide and at the interface between the oxide and the rest of the semiconductor. These add up and shift the transistor towards the "off" state, says Narukiyo. To compensate, the new receiver design minimizes the use of PMOS, replacing these transistors with other elements such as inductors that don't have an oxide layer. NMOS transistors are more resilient, says Narukiyo, because positive charges trapped in the oxide are to some extent canceled out by negative charges that get trapped at the interface.

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[2] Christopher Plain, The Debrief, "his New Invention Will Let Robots Work Directly Inside a Failed Nuclear Reactor," March 26, 2026, https://thedebrief.org/this-new-invention-will-let-robots-work-directly-inside-a-failed-nuclear-reactor/

[3] The gray (Gy) is the SI unit of absorbed dose of ionizing radiation, measuring the amount of energy deposited by radiation in a unit mass of matter. One gray equals 1 joule of radiation energy per kilogram of material. https://en.wikipedia.org/wiki/Gray_%28unit%29

The transistors, silicon MOSFETs (metal-oxide semiconductor field-effect transistors), contain an oxide layer that's particularly vulnerable to radiation damage. Blasts of gamma rays can trap positive charges in the oxide, degrading the device's performance and causing errors. So, using fewer of them minimizes the problem. The researchers also made each transistor's gate longer and wider. The gate controls the flow of current—longer, wider gates perform better under exposure to radiation.

Narukiyo and his team measured the performance of the receiver before exposure to radiation, and again after blasting it with a total dose of 300 kGy and then 500 kGy. Before being irradiated, it showed comparable performance to typical Wi-Fi receivers. After reaching the highest radiation dose, the gain of the receiver had decreased by about 1.5 decibel.

Narukiyo says the receiver is hardened enough, and now he hopes to improve its performance. He's also working on a transmitter, which would allow for two-way communications. This is more challenging due to the need to produce high levels of current to generate the Wi-Fi signal. He says an earlier version he tried was broken by a 300 kGy dose. The group is exploring using other semiconductors, such as diamond, to toughen the transmitter.

2.2.1. Degrees of Rad-Hardening

There are degrees of radiation-hardening. If you are interested in the subjects covered by this paper, you, by necessity, must be interested in radiation-hardening, although bots for radioactive environments are only one application of electronics that require radiation hardening. For instance, if you are designing applications that are going into orbital- or outer-space, these each need to be hardened, but to different (generally lower) degrees.

Your author found an article that explored those differences and it is reference below, and used for the text below.[4]

In the high-tech world of military applications, where precision, endurance, and reliability are paramount, electronic components need to function in some of the most challenging environments. One of the often-overlooked challenges these components face is radiation. From satellites orbiting Earth to deep space probes, and even in certain terrestrial applications, radiation can wreak havoc on electronic devices.

To counter this, two primary approaches have emerged: radiation-hardened (often referred to as rad-hard) and radiation-tolerant. This article delves deep into these terminologies, highlighting their differences and applications, ensuring you make an informed decision when selecting components for your next project.

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[4] Dan Taylor, "Military Embedded Systems," August 10, 2023, "Rad-Hard vs. Rad-Tolerant: A Guide to the Differences and Applications in Military Electronics," https://militaryembedded.com/comms/satellites/rad-hard-vs-rad-tolerant-a-guide-to-the-differences-and-applications-in-military-electronics

2.2.2. Definitions: Rad-Hard vs. Rad-Tolerant

First, it's helpful to understand what we are talking about when we use the terms rad-hard and rad-tolerant.

2.2.2.1. Rad-Hard (Radiation Hardened)

When we talk about radiation-hardened or rad-hard devices, we are referring to electronics specifically designed and produced to withstand intense radiation levels. These components undergo rigorous manufacturing and testing processes to ensure they can resist radiation effects over prolonged periods. Whether in the core of a nuclear reactor or in the depths of space where cosmic rays abound, rad-hard devices aim to function without faltering. Their integrity is maintained even under extreme radiation, making them invaluable in critical missions where failure is not an option.

2.2.2.2. Rad-Tolerant

On the other side of the spectrum, we have radiation-tolerant electronics. These devices can also resist radiation, but they're not built to withstand the same intensity or duration as their rad-hard counterparts. They are a middle ground between standard electronics and rad-hard devices, designed for environments where radiation is present but not as intense or long-lasting. Think of them as the electronics that have undergone special training to survive in challenging conditions but not quite the elite training of rad-hard components. Their sweet spot lies in shorter missions or applications where the radiation dose is substantial but not extreme.

2.2.2.3. Differences Between Rad-Hard and Rad-Tolerant

While both rad-hard and rad-tolerant devices offer resistance to radiation, it's crucial to understand the nuances that set them apart: duration of the resistance, the radiation exposure levels they can withstand, expectations for enduring single event effects (SEE), and qualification and testing.

2.2.2.4. Duration of Resistance

Rad-Hard: Designed for the long haul, these devices are built to resist intense radiation levels over extended periods. They are the marathon runners of the radiation world, able to endure without degradation or loss of functionality.

Rad-Tolerant: Tailored for shorter stints, rad-tolerant electronics are perfect for missions or applications with a lifecycle of typically five years or less. They're more like sprinters, built to perform optimally in short, intense bursts.

2.2.2.5. Radiation Exposure Levels

Rad-Hard: These devices are the heavyweights, designed to handle exceptionally high levels of radiation. Their structure and materials are chosen and optimized to endure the harshest radiation environments.

Rad-Tolerant: Suited for milder radiation climates, these devices can typically handle radiation exposure ranging from 10-30 krad (Si). In some cases, they might be tweaked to withstand slightly higher doses, but they won't match the resilience of rad-hard devices.

2.2.2.6. Single Event Effects (SEE) Expectations

Rad-Hard: Rad-hard devices are meticulously designed to minimize both destructive and transient SEE. Every scenario is considered, ensuring that even unexpected radiation spikes won't cause malfunctions.

Rad-Tolerant: While these devices are also designed to resist SEEs, they're more susceptible to non-destructive events. These can sometimes be managed with system-level safeguards like redundancy, Error Detection and Correction (EDAC), and filtering. However, they are more vulnerable to destructive SEEs which can, in some cases, result in early mission termination.

2.2.2.7. Qualification & Testing

Rad-Hard: No stone is left unturned when qualifying rad-hard devices. Every wafer lot undergoes rigorous testing, ensuring that each component meets the highest radiation resistance standards.

Rad-Tolerant: These devices undergo a more streamlined, automotive-like qualification process, with one-time radiation characterization. Although they are tested to ensure radiation tolerance, the process is less exhaustive than with rad-hard devices, reflecting their shorter operational expectancy and less demanding radiation specifications.

Final author's comment: The reference 2 author does a deep-dive on these standards. Although I thought the readers of this article could use a basic understanding of these, I did not think they needed a masters-course, so I've finished following this trail here. If any readers wish to go further, go to the above reference and follow the link.